

Regulation of the X-ray luminosity of clusters of galaxies by cooling and supernova feedback

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Clusters of galaxies are thought to contain about ten times as much dark matter as baryonic matter¹. The dark component therefore dominates the gravitational potential of a cluster, and the baryons confined by this potential radiate X-rays with a luminosity that depends mainly on the gas density in the cluster’s core.² Predictions of the X-rays’ properties based on models of cluster formation do not, however, agree with the observations. If the models ignore the condensation of cooling gas into stars and feedback from the associated supernovae, they overestimate the X-ray luminosity because the core gas is too high. An early episode of uniformly distributed supernova feedback could rectify this by heating the uncondensed gas and therefore making it harder to compress into the core^{3–11}, but such a process seems to require an implausibly large number of supernovae^{6,8,12–14}. Here we show how radiative cooling of intergalactic gas and subsequent supernova heating conspire to eliminate highly compressible low-entropy gas from the intracluster medium. This brings the core entropy and X-ray luminosities of galaxy clusters into agreement with the observations, in a way that depends little on the efficiency of supernova heating in the early Universe.

Numerical simulations of cosmological structure formation show that the dark-matter potential wells of clusters are quite similar in shape across a wide mass range¹⁵. A cluster’s mean mass density within the virial radius r_v is roughly 200 times ρ_{cr} , the critical density for closing the universe, with a dark-matter density distribution $\rho_{DM} \propto [r(1 + cr)^2]^{-1}$, where r is the radius in units of r_v and $c \sim 4 - 10$ is a parameter governing the concentration of dark matter toward the centre of the cluster. In the absence of radiative cooling and supernova heating, the gas density in such simulated clusters follows nearly the same profile¹⁶, with some additional flattening for $r \lesssim 1/c$.

If all clusters had similar gas density distributions, then cluster temperature would scale as $T \propto \rho_{cr} r_v^2$ and X-ray luminosity would scale as $L \propto \Lambda \rho_{cr}^2 r_v^3$, where Λ is the cooling rate per unit density of the hot gas. At typical cluster temperatures ($T > 2$ keV), free-free emission dominates the cooling, so $\Lambda \propto T^{1/2}$ and we would expect $L \propto T^2$. Instead, the observed power-law index^{17–19} in the relation $L \propto T^b$ is $b \approx 2.6 - 2.9$, meaning that low-temperature clusters and groups of galaxies are far less luminous than expected. This luminosity deficit is also evident in the low

level of the unresolved ~ 1 keV X-ray background, which is an order of magnitude smaller than predicted by cosmological simulations without radiative cooling or supernova heating^{20–23}.

The X-ray luminosities of low-temperature clusters are unexpectedly small because their gas is less centrally concentrated than in hotter clusters, an effect that has been attributed to a universal minimum entropy level in intracluster gas resulting either from supernova heating^{5,9–11}, from heating by active galactic nuclei⁸, or from radiative cooling^{8,12,24,25}. A lower limit to intracluster entropy steepens the relationship between luminosity and temperature because the shallower potential wells of low-temperature clusters are less able to overcome the resistance to compression owing to that minimum entropy. Both observations⁵ and theoretical models^{6,10,11,20,21} have established that a core entropy level corresponding to $S \sim 100 - 200 \text{ keV cm}^2$ can account for the observed slope of the $L:T$ relation and the low level of the ~ 1 keV background.

This entropy scale emerges most naturally from considerations involving radiative cooling. For any cluster of temperature T , one can compute the specific entropy level at which a gas parcel would radiate away its thermal energy in a time equivalent to the age of the Universe. Figure 1 shows that locus in the entropy-temperature plane for a typical cluster heavy-element abundance of 30% of the solar value. The locus for this typical abundance lies in the $100 - 150 \text{ keV cm}^2$ range for $T < 2 \text{ keV}$ and rises in proportion to $T^{2/3}$ at higher temperatures. Note that the measured core entropies of clusters and groups⁵ closely track the cooling locus.

The remarkable correspondence between the threshold entropy for cooling (S_c) and observations of core entropy suggests the following picture for the evolution of the intracluster medium. We can consider the medium to consist of independent gas parcels, each with its own entropy history. The luminosity of a sufficiently relaxed cluster, in which entropy increases monotonically with radius, is then completely determined by the shape of its potential well $\rho_{DM}(r)$ and the distribution of specific entropy among its gas parcels. In the context of hierarchical merging, a parcel’s entropy history proceeds like this: each merger event affecting the parcel raises its entropy to some new value S_i , and as the gas relaxes after the merger, the parcel’s temperature will approach T_i , the characteristic temperature of its new dark-matter halo. A parcel’s trajectory in the $S - T$ plane is thus defined by a series of points (S_i, T_i) that proceed upward and to the right in a diagram like Figure 1.

Now consider the effect of the cooling locus, which creeps vertically up the diagram as time progresses. If a parcel’s entropy trajectory always remains above this threshold, it will never cool. However, parcels of gas that find themselves below the cooling threshold as structure develops begin to condense and form stars. Shortly thereafter, supernovae heat the neighbouring gas with an efficiency that remains unknown, adding entropy that tends to suppress further cooling and condensation. Stars will continue to form and supernovae will continue to explode until there is no more gas below the cooling threshold; then both processes must cease. Thus cooling and whatever feedback accompanies it act in tandem to eliminate gas parcels with $S < S_c$, inevitably creating an entropy floor at the cooling threshold.

This model leads to an $L:T$ relation that closely matches cluster observations. Suppose that both the gas and dark matter density are proportional to $[r(1 + cr)^2]^{-1}$ in the absence of cooling. Then we can compute the unmodified entropy distribution $M_g(S)$, the mass of gas with specific entropy less than S , and the inverse relation $S(M_g)$. When cooling is allowed to operate, gas parcels with $S < S_c$ are subject to condensation, and any subsequent feedback is targeted directly at those low-entropy gas parcels. If feedback is inefficient, condensation will remove this gas from the intracluster medium. If feedback is highly efficient, supernova heating will raise the entropy of this gas to $S \gg S_c$, and it will convect to the outer regions of the cluster. In either limit, the modified entropy distribution approaches $S^*(M_g) = S(M_g + M_c)$, where $M_c \equiv M_g(S_c)$. Figure 2 illustrates the $L:T$ relation that we compute when we allow gas with entropy distribution $S^*(M_g)$ to be in hydrostatic equilibrium with the dark matter potential, assuming a Hubble constant of $100 h \text{ km s}^{-1} \text{ Mpc}^{-1}$ with $h = 0.65$ and a baryon fraction $0.02 h^{-2} \Omega_M^{-1}$ with a total matter density $\Omega_M = 0.33$. (Using an alternative modified entropy distribution, $S^*(M_g) = S(M_g) + S_c$, leads to similar results.)

The $L:T$ relation we derive from the cooling threshold agrees not only with observations but also with cluster simulations²⁶ that include radiative cooling but no supernova heating. That agreement underlines an important feature of this model: the $L:T$ relation it predicts is insensitive to the efficiency of supernova heating. Any combination of cooling and feedback that truncates the unmodified entropy distribution at the entropy scale S_c will lead to a similar $L:T$ relation. In that sense, the relation determined by the cooling threshold represents the upper envelope to all $L:T$ relations consistent with the age of the universe. Extreme amounts of feedback could further lower the luminosity, but apart from relatively small amounts of low-entropy gas that have not yet completely cooled²⁷, the luminosity of a cluster cannot substantially exceed this relation.

Despite the spherical symmetry of the end state, the cooling, condensation, and feedback processes that regulate the $L:T$ relation are not restricted to the cluster’s core. In hierarchical models of structure formation, the spatial distribution of specific entropy is initially quite complex. If cooling is not allowed to operate, the highest-density, lowest-entropy gas parcels will eventually find their way into the cluster core. However, in the real Universe, this low-entropy gas condenses and forms galaxies long before it reaches the centre of the cluster. Much of the condensation and feedback that ultimately determines a cluster’s luminosity therefore pre-dates the epoch of cluster formation. Only modest quantities of gas remain below the cooling threshold in most present-day clusters, where they collect into centrally-focused cooling flows.

If this interpretation of the $L:T$ relation is correct then the level of the entropy floor in clusters ($\sim 100 - 200 \text{ keV cm}^2$) conveys little information about the efficiency of supernova heating in the early Universe. That information is more directly reflected in the fraction of baryons that have formed stars. A large proportion of the baryons that are now in clusters were associated with objects of less than 10^{12} solar masses at $z \approx 2$. At that time, the cooling threshold in a dark-matter halo of 10^{12} solar masses would have been $\sim 10 \text{ keV cm}^2$, and virtually all the baryons in those haloes were below that threshold²⁸. Some form of feedback, probably supernovae,

prevented most of these baryons from condensing. Once feedback drives uncondensed gas to high entropy and low density, merger shocks can more easily maintain it above the cooling threshold. Detailed computations tracing the entropy history of each gas parcel through the series of cooling, feedback, and merger events leading to the final cluster will therefore be needed to relate the supernova heating efficiency to the fraction of baryons now in stars.

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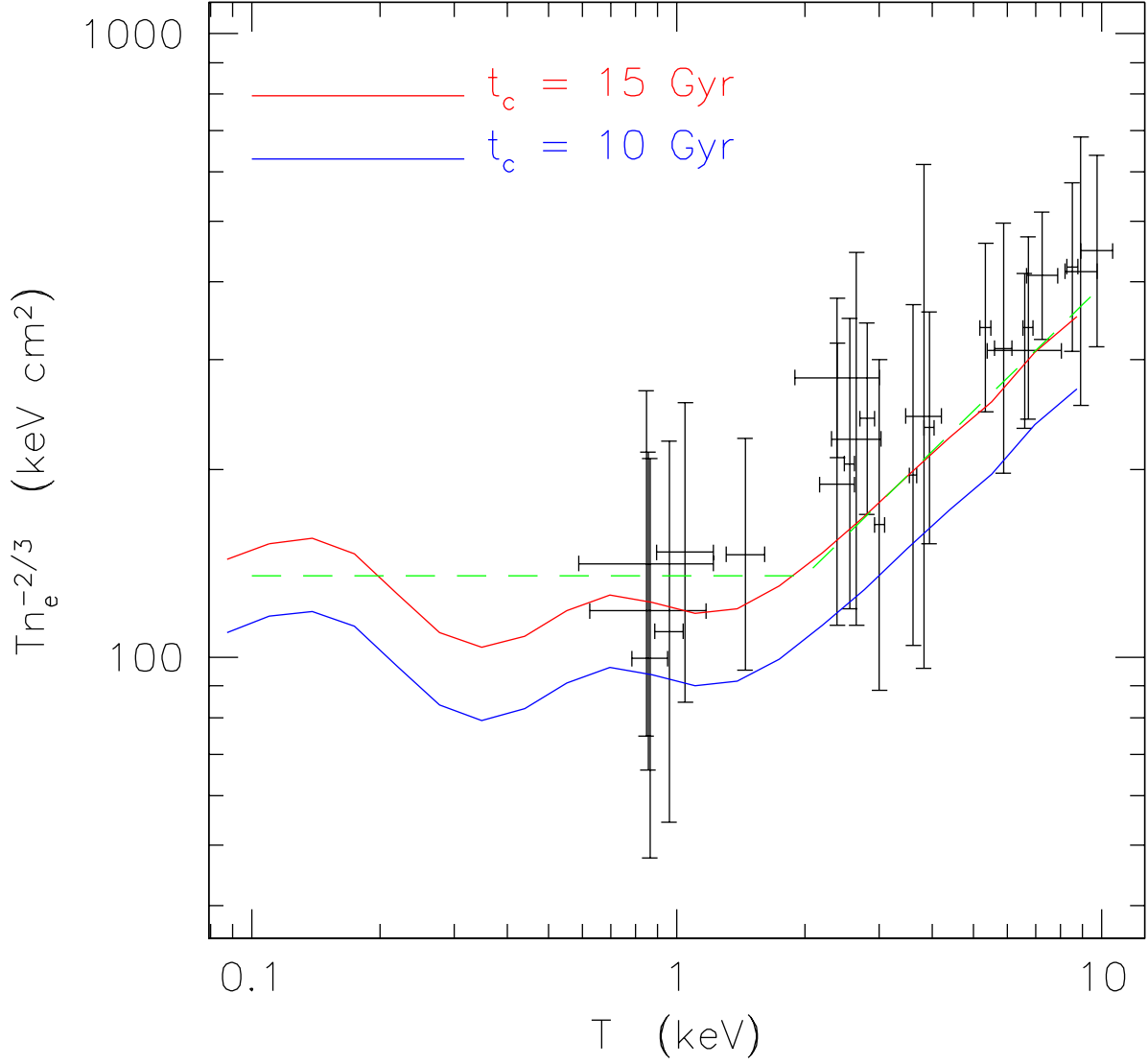


Fig. 1.— Threshold entropy for cooling within the age of the universe. The solid lines show the specific entropy $S = T n_e^{-2/3}$, where n_e is the electron density, at which gas of temperature T will cool within 15 Gyr (red) and 10 Gyr (blue) for elemental abundances of 30% solar. (The usual thermodynamic entropy for an ideal monatomic gas is proportional to $\ln S$.) Note that the core entropy levels in clusters measured at the core radius $0.1 r_v$ (ref. 5) track the cooling threshold for typical cluster heavy-element abundances of 30% solar. Within that core radius many clusters contain gas whose entropy lies below the cooling threshold, but the luminosity of that relatively small amount of low-entropy gas usually contributes only modestly to the overall luminosity of the cluster.¹⁸ The dashed green line indicates the entropy threshold S_c used to determine the $L:T$ relation in Figure 2.

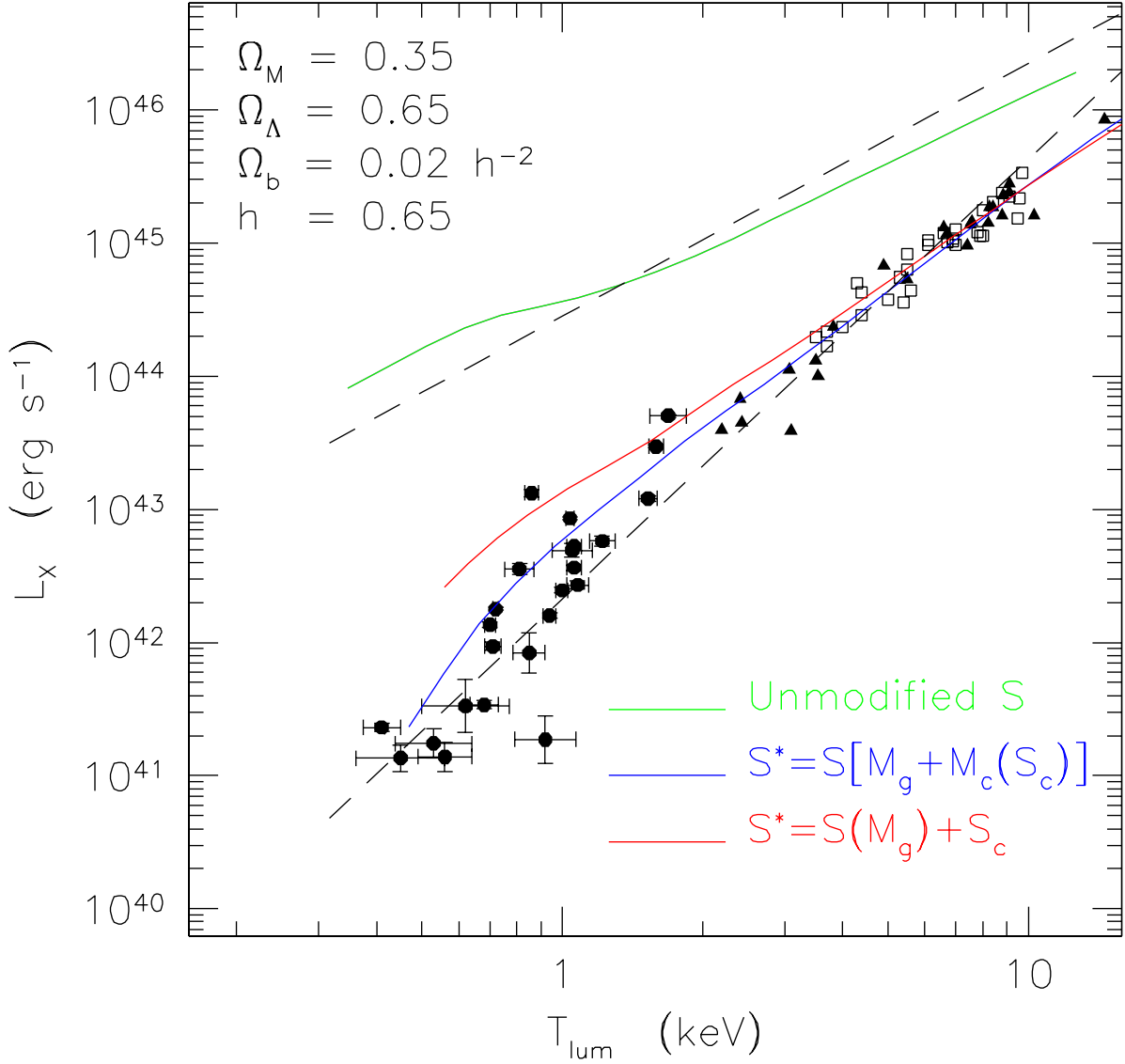


Fig. 2.— Relation between bolometric X-ray luminosity L_X and luminosity-weighted temperature T_{lum} in clusters and groups of galaxies. Green line, the $L:T$ relation from the unmodified entropy distribution $S(M_g)$ for concentration factors corresponding to model $S_{1.2}$ from ref. 29. Blue line, the $L:T$ relation derived from our primary cooling-threshold model, in which $S^* = S[M_g + M_c(S_c)]$ (see text for details) for the threshold entropy S_c indicated by the dashed green line in Figure 1. Red line, the $L:T$ relation for an alternative modified-entropy model in which $S^* = S(M_g) + S_c$. Dashed lines, fits to numerical simulations²⁵ of clusters with (lower line) and without (upper line) radiative cooling. Triangles, measurements of L_X and T from a compilation of cluster data¹⁹; open squares, additional cluster data¹⁸; filled circles, group data³⁰. All data and models are normalized to a Hubble constant of $h = 0.65$. The cooling-threshold model naturally accounts for the $L:T$ relation in a standard Λ -dominated cosmology (total matter density, $\Omega_M = 0.35$; dark-energy density, $\Omega_\Lambda = 0.65$; baryon density, $\Omega_b = 0.02h^{-2}$) without any adjustable parameters.